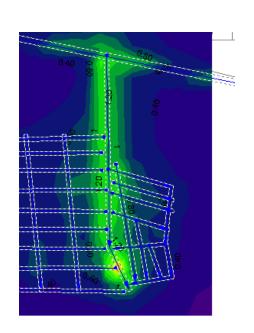# Applications of Mobile Sensing

Lagrangian Sensor Systems Laboratory
UC Berkeley
Electrical Engineering and Computer Sciences, Systems Engineering, Mechanical Engineering, Industrial Engineering and Operations Research

Los Alamos, 03/23/2010

The edge of the "classical" sensing paradigm

In the "classical" sensing paradigm, we
– **Use the best / most accurate sensors**
– **Deploy a dedicated monitoring and data gathering infrastructure**
– **Maximize coverage of the sensor network**
– **Maximize autonomy of the platform (robots)**

Example: autonomous water sensors patrolling water distribution infrastructure
– **Floating robots**
– **Built for a specific application**
– **Goal: no human involved**
– **Possess suite of sensors**
   – **Salinity**
   – **Trubidity**
   – **Contaminants**
   – **Etc.**
– **2010 Target: 100 autonomous in the Sacramento Delta and San Francisco Bay**

User generated content: sensor-free sensing

An example in which user generated content can be more can be more efficient than the proper tool.

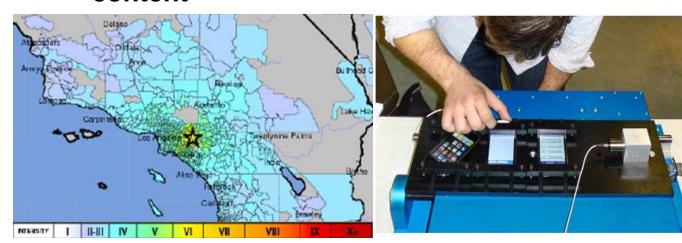- An appropriate sensor to measure an earthquake is an accelerometer
- USGS has deployed sensor arrays in the US
- Today, most smartphones have accelerometers
  - Using them for earthquake monitoring is challenging
  - Deploying a dedicated infrastructure is expensive
- Yet Twitter can provide first alert of the type "Did you feel it" based on user generated content

Web 2.0

Emergence of the mobile internet

- Internet accesses from mobile devices skyrocketing
- Mobile devices outnumber PCs by 5:1
- 1. 5 million devices/day (Nokia)
- Redefining the mobile market: Google, Apple, Nokia, Microsoft, Intel, IBM, etc.
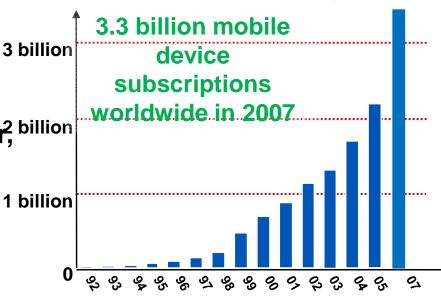- Open source computing: Symbian Foundation, Android, Linux

Sensing and communication suite

- GSM, GPRS, WiFi, bluetooth, infrared
- GPS, accelerometer, light sensor, camera, microphone

Smartphones and Web 2.0

- Context awareness
- Sensing based user generated content

3.3 billion mobile device subscriptions worldwide in 2007

3 billion

2 billion

1 billion

0

92 93 94 95 96 97 98 99 00 01 02 03 04 05 07

[Courtesy J. Shen, Nokia Research Center Palo Alto]

Outline

Mobile Century traffic experiment

- Issues with mobile sensing in the context of traffic
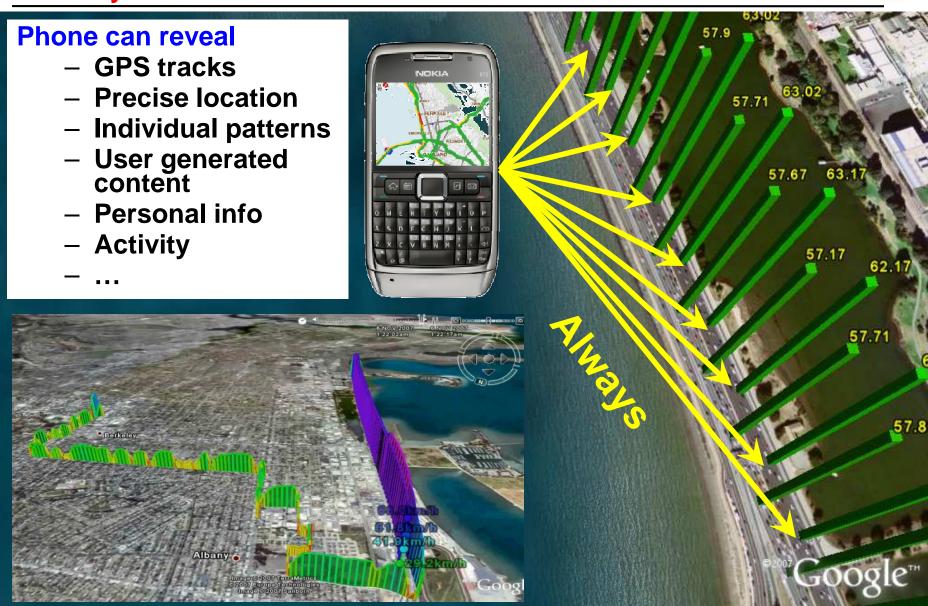- Mobile Century experiment results

Mobile floating sensor networks

- Background
- Applications

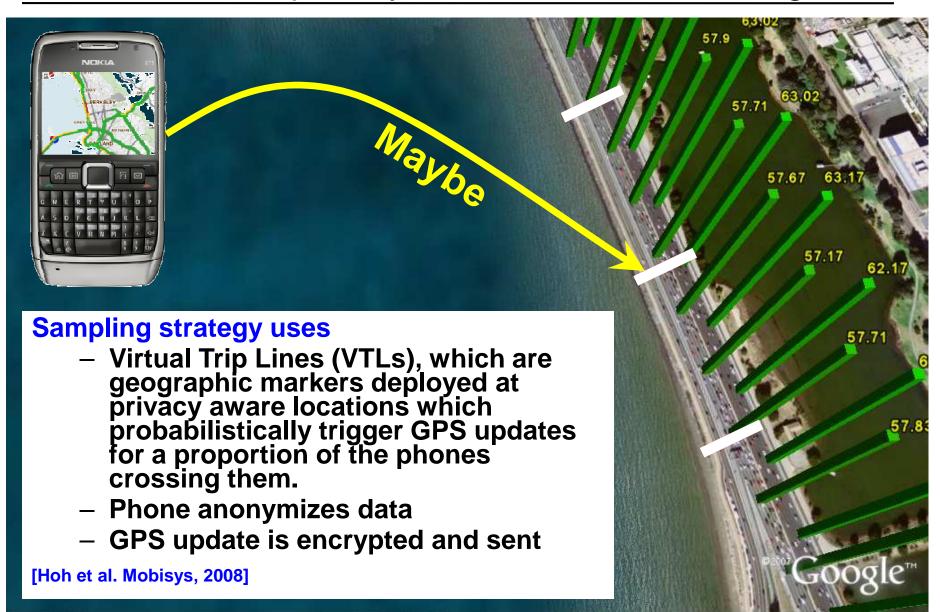**Pollution and noise estimation using smartphones**

Conclusion

Privacy issues for location based services

Phone can reveal
- GPS tracks
- Precise location
- Individual patterns
- User generated content
- Personal info
- Activity
- …

Always

Data collection: spatially aware traffic monitoring

Maybe

Sampling strategy uses
  - **Virtual Trip Lines (VTLs), which are geographic markers deployed at privacy aware locations which probabilistically trigger GPS updates for a proportion of the phones crossing them.**
  - **Phone anonymizes data**
  - **GPS update is encrypted and sent**

[Hoh et al. Mobisys, 2008]

Tradeoffs (summary)

Privacy considerations
- – **Sampling strategy**
- – **Randomization of the sampling**
- – **Anonymization of the data**
- – **Encryption of the data**
- – **Local computations (onboard the phone)**

Accuracy considerations, and data to push the estimation further
- – **Full trajectory collection**
- – **Re-identification (day to day)**
- – **Additional context collection (jam, pictures, other sensors)**
- – **Tower information**

Hardness of estimation

Privacy intrusion
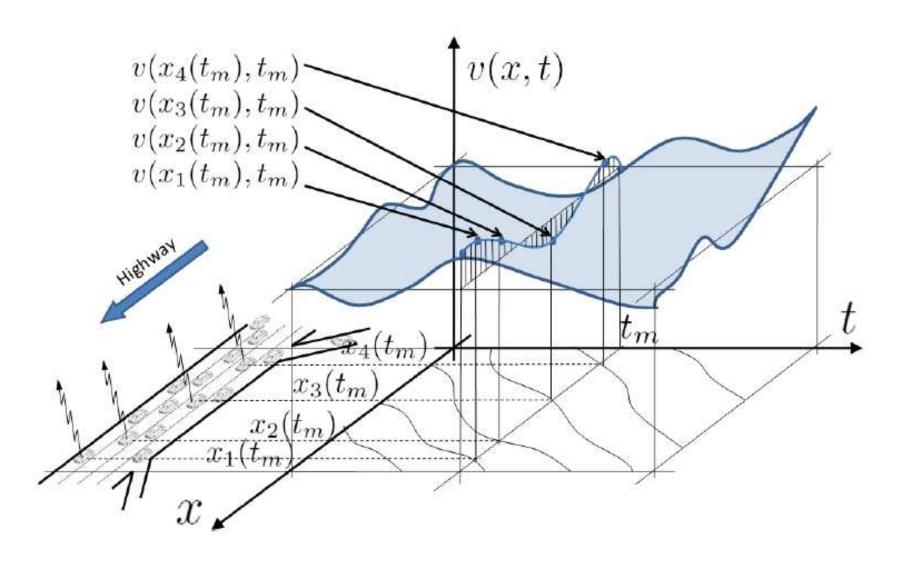
Estimation results
- – **Patterns**
- – **Travel time**
- – **Aggregate data**

Individual trajectories
- – **Inference from patterns**
- – **Reconstruction?**

Modeling issues: Data assimilation/inverse modeling

How to incorporate Lagrangian (trajectory based) and Eulerian (control volume based) measurements in a flow model.

Data assimilation in the context of traffic flow

Recursive solution:

Ensemble Kalman Filtering for speed or density contour estimation

Optimization based methods:

Convex optimization-based methods for travel time estimation, sensor fault detection, consistency analysis

Machine learning based methods:

STARMA methods for link travel time estimation

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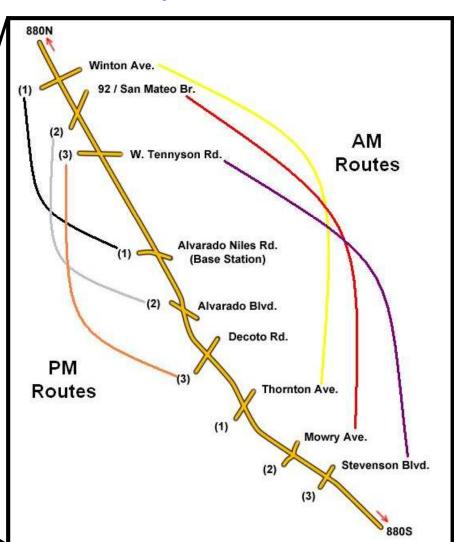
Prototype experiment: *Mobile Century*

Experimental proof of concept: the *Mobile Century* field test

- **February 8th 2008**
- **I80, Union City, CA**
- **Field test, 100 cars**
- **165 Berkeley students drivers**
- **10 hours deployment,**
- **About 10 miles**
- **2% - 5% penetration rate**

A glimpse of *Mobile Century* (February 8ᵗʰ, 2008)

A glimpse of *Mobile Century* (February 8th, 2008)

Mobile Century validation video data collection

Video data:
- Vehicles counts
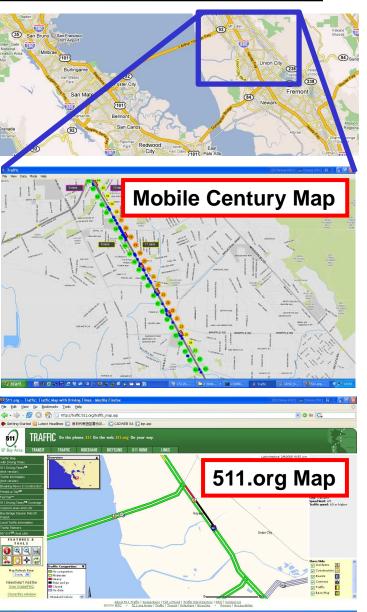- Travel time validation
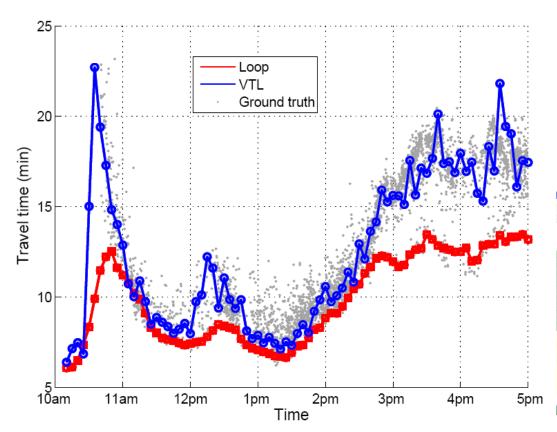
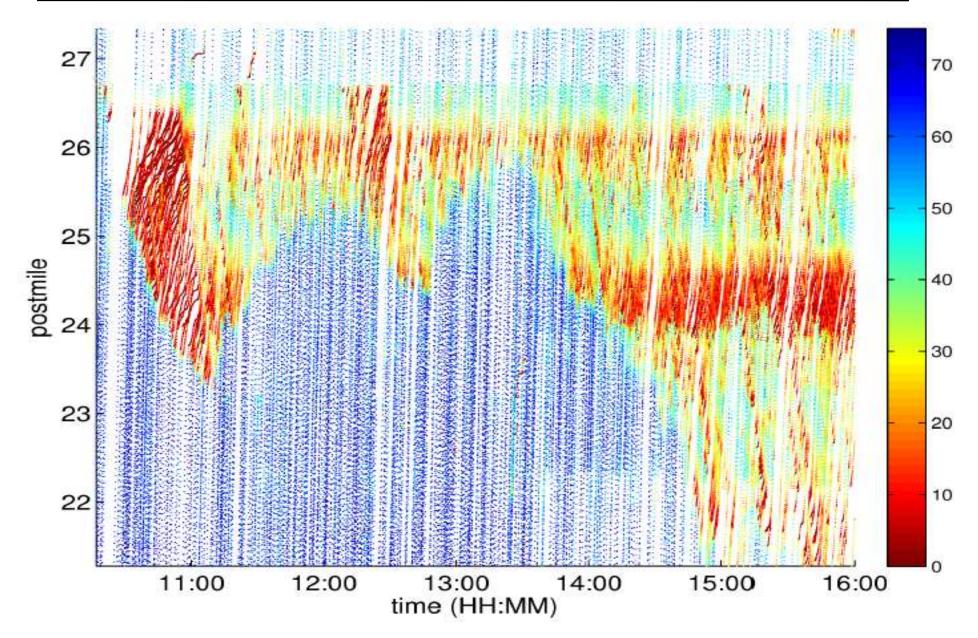# Validation of the data (video)

Travel time predictions

- – **Can be done in real time at a 2% penetration rate of traffic**
- – **Proved accurate against data from www.511.org, with higher degree of granularity**
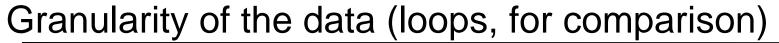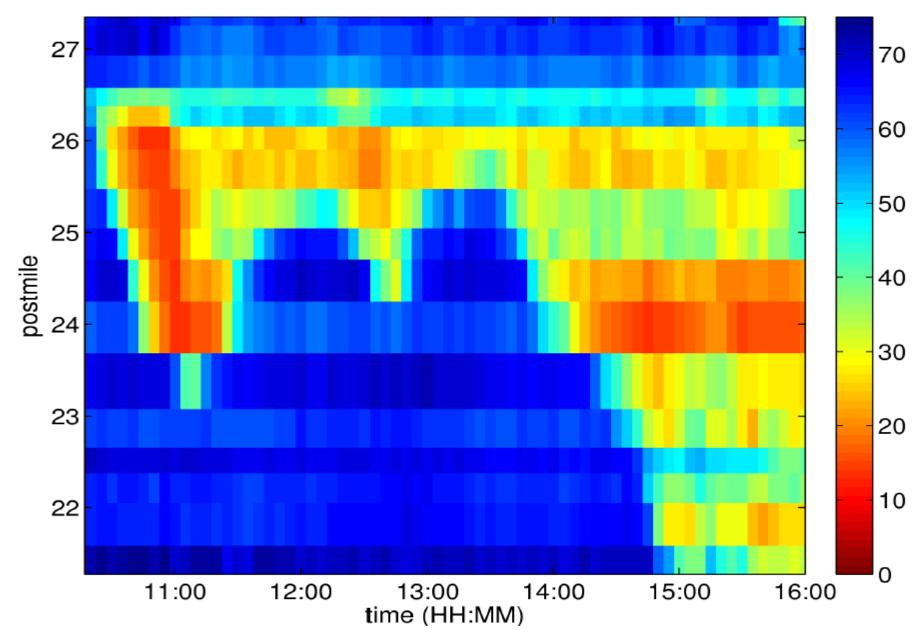

Mobile Century Map

511.org Map

Granularity of the data (GPS data)
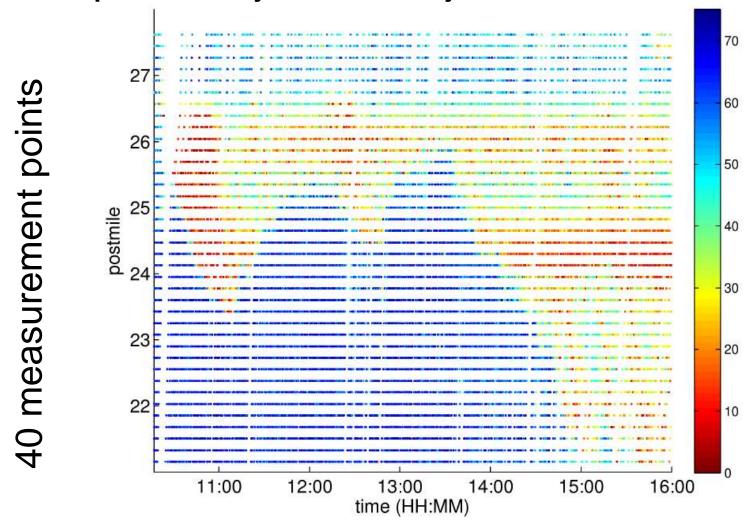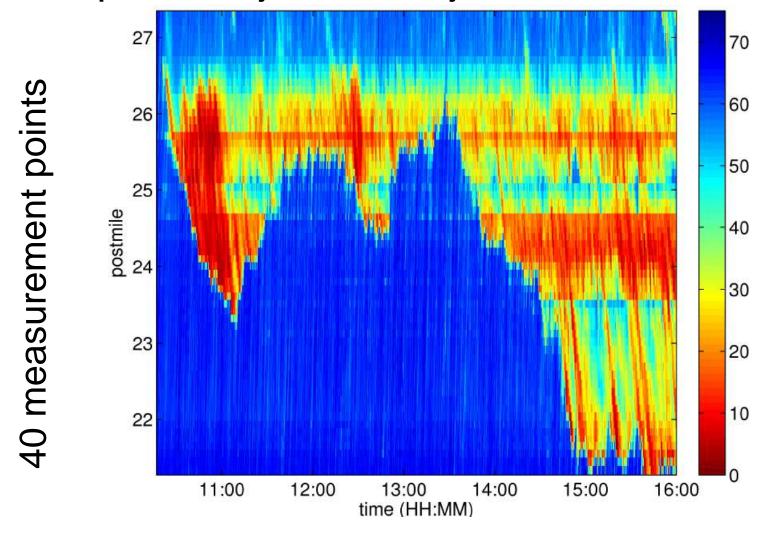
Granularity of the data (loops, for comparison)

Flow reconstruction (inverse modeling)

Physical model and data assimilation enable state estimation
- Works even with low penetration rate
- Interpolation will just not do the job

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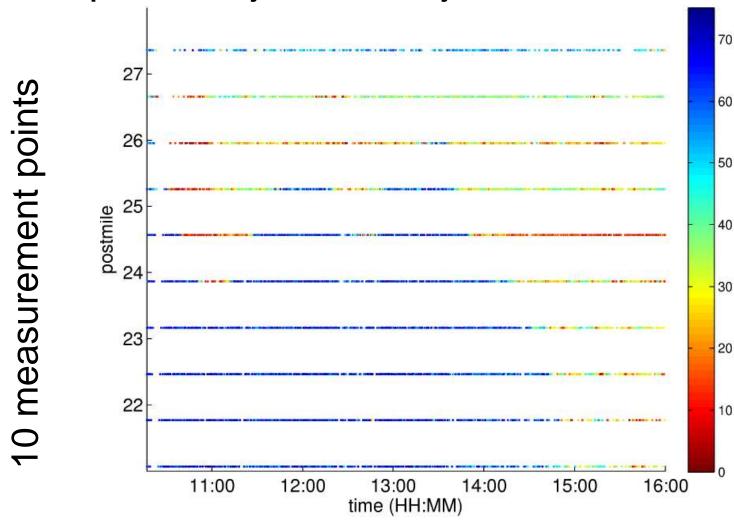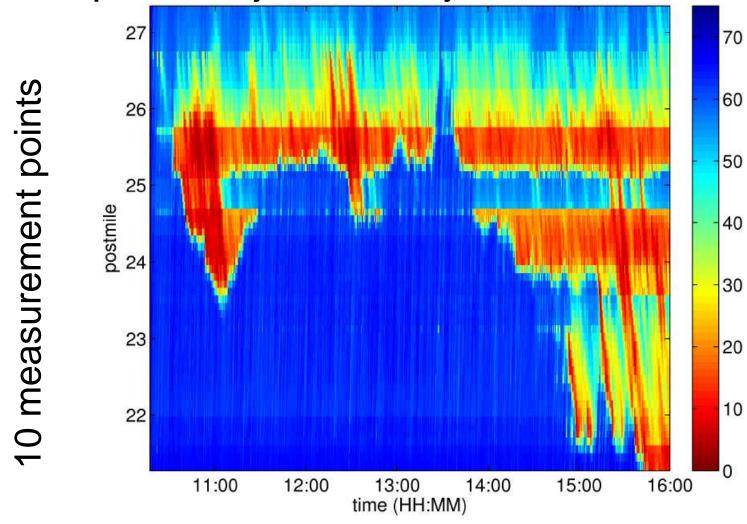
- – **Works even with low penetration rate**
- – **Interpolation will just not do the job**
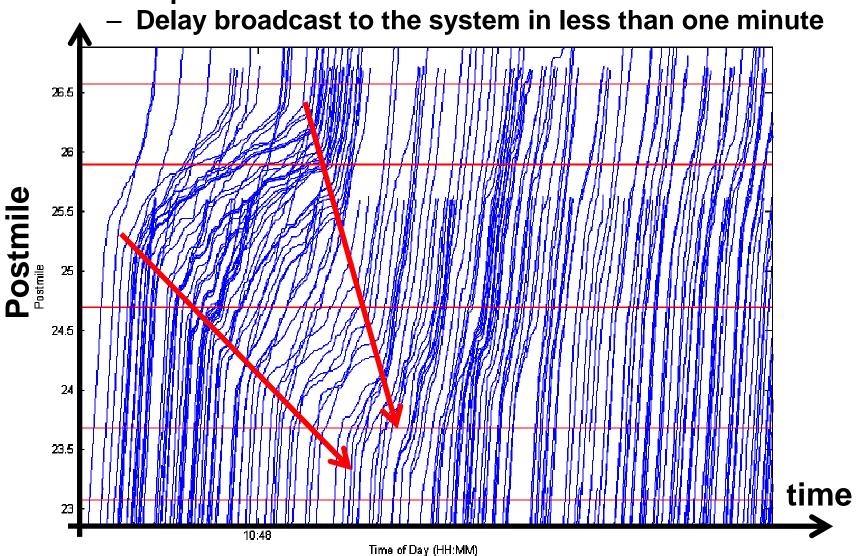
Revealing the previously unobservable

5 car pile up accident (not Mobile Century vehicles)
– **Captured in real time**
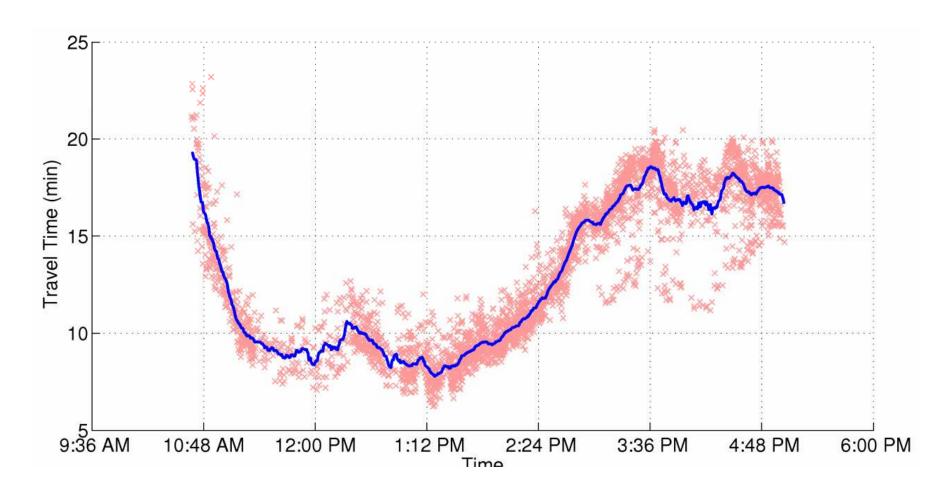– **Delay broadcast to the system in less than one minute**

Impact on travel time estimation

Mobile Century example
- **Red dots: true travel time computed from license plate re-ID**
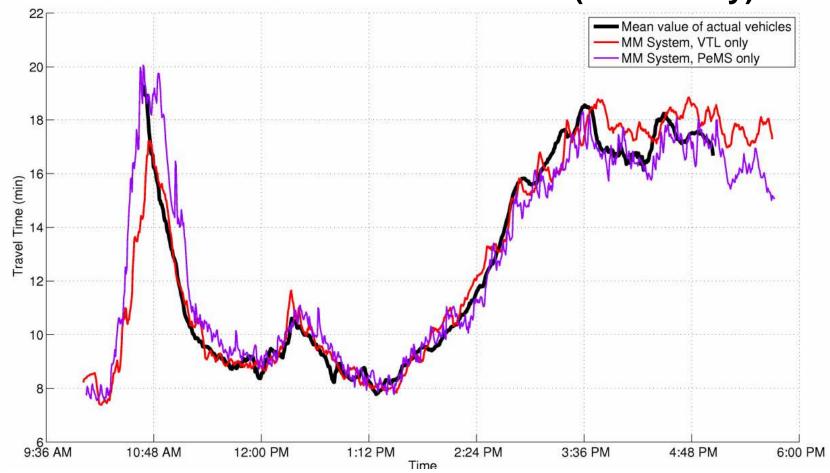- **Blue: average travel time**

Impact on travel time estimation

Mobile Century (MC) example (cont')
- **Black: average travel time (license plate based)**
- **Red: MC model estimation results (phones only)**
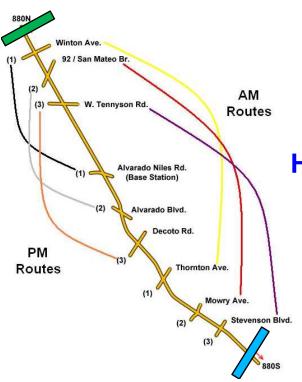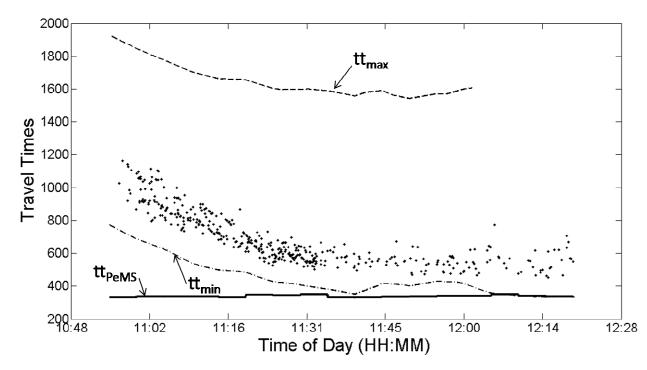- **Blue: MC model estimation results (PeMS only)**

Bounds on travel time (PeMS)

Outflow loop

Inflow loop

**How to decrease the uncertainty on a parameter /
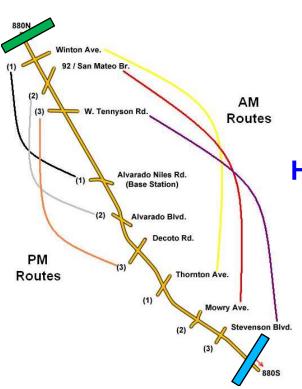state variable (travel time) with inverse modeling**
  – **2 sensors**
  – **One accident in the middle, not captured by
    the sensors**
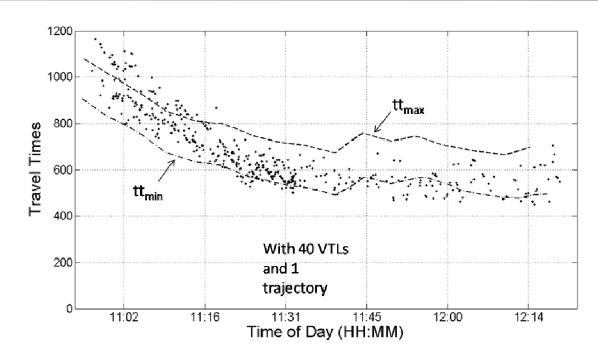 – **One can still estimate bounds on congestion**

Bounds on travel time (PeMS and phones)

Outflow loop

Inflow loop

How to decrease the uncertainty on a parameter / state variable (travel time) with inverse modeling

- **2 sensors**
- **One accident in the middle, not captured by the sensors**
- **One can still estimate bounds on congestion**

Outline

Mobile Century traffic experiment

    - **Issues with mobile sensing in the context of traffic**
    - **Mobile Century experiment results**

Mobile floating sensor networks

    - **Background**
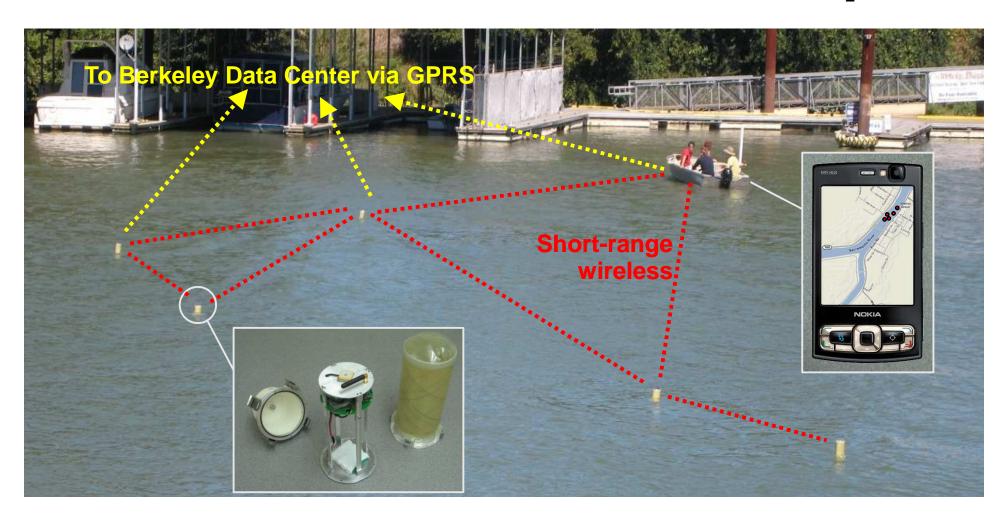   - **Applications**

Pollution and noise estimation using smartphones

Conclusion

Floating [Lagrangian] sensor network
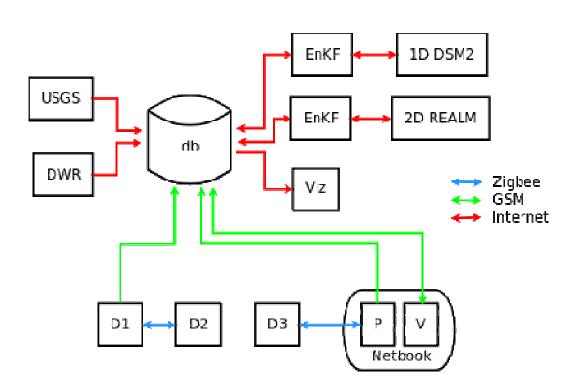
Current fleet: 10 passive GPS floats (courtesy M. Stacey), 10 GPS/wireless enabled drifters (manufactured at Berkeley)
Target (2010) fleet of 100 (potentially using Android phones)
Potential additional sensors: salinity, temperature, dissolved O_2

Berkeley floating sensor package

Mechanical design

    Passive floating sensor
    Vertical cylinder, 17" tall, 5" diameter
    Fleet of 10
    Mission time: 24 hours

Berkeley floating sensor package

Onboard hardware
  - Communications: GSM module, ZigBee radio
  - GPS receiver w/ carrier phase at 1Hz
  - Temperature/electroconductivity sensor in exposed lower hull
  - Embedded computer (XScale based PXA270, running Linux)
  - 200 g LiPo battery, 600 g Pb ballast
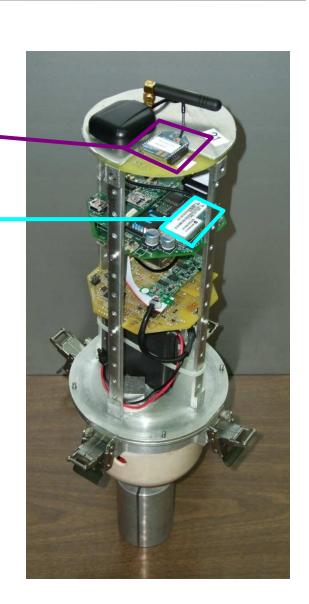 - 1 GB data storage

Berkeley floating sensor package

Zigbee radio

GSM module

Onboard hardware
- **- Communications: GSM module, ZigBee radio**
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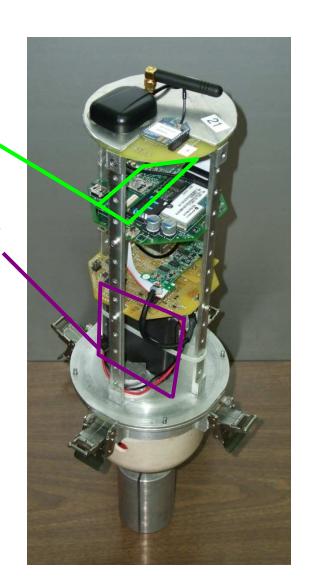- **- 1 GB data storage**

Berkeley floating sensor package

Gumstix embedded computer

Battery

Onboard hardware
   - **Communications: GSM module, ZigBee radio**
   - **GPS receiver w/ carrier phase at 1Hz**
   - **Temperature/electroconductivity sensor in exposed lower hull**
   - **Embedded computer (XScale based PXA270, running Linux)**
   - **200 g LiPo battery, 600 g Pb ballast**
   - **1 GB data storage**

Mobile Berkeley floating sensor package

Mobile floating sensor

Designed for manufacturability: standard parts, less custom machining

Two propellers in differential drive configuration

Internal water bag for buoyancy control

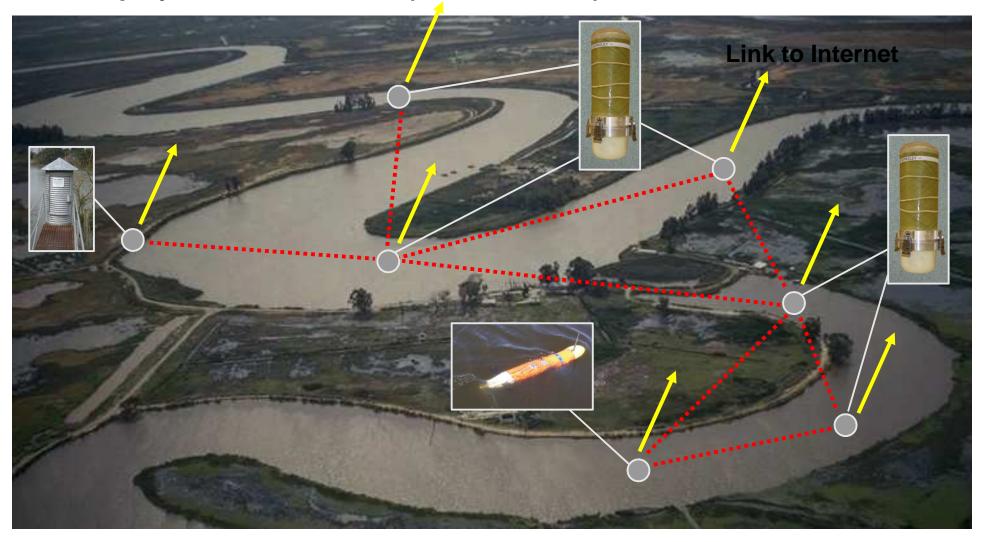First round of prototyping happening now; planning a fleet of 100

Vision: progressive instrumentation of the Delta

Development of an autonomous monitoring system

Dedicated feeds (static sensors)

Deployable data sources (AUVs, drifters)

Link to Internet

Data assimilation: process and validation

minimize: $\displaystyle\sum_{d\in\text{drifters}} \int_0^T \|\vec{u}(\vec{x}_d(t),t) - \vec{u}_d^{\text{measured}}(t)\|^2 dt \quad + \text{regularization terms}$

s.t.: $\text{PDE}(\vec{u})$
$\text{BC}(\vec{u})$
$\text{IC}(\vec{u})$

Variation data assimilation: **Minimize the L2 error between the measurements and the outputs of the model, over the considered period of time.**

Recursive solution: Kalman Filtering

Linear equations and scheme
- **Quadratic program**
- **Kalman filtering**

Nonlinear equations and scheme
- **Nonlinear program**
- **[Extended / Ensemble] Kalman filtering**

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Response to unanticipated events could be improved using mobile sensing, for example in the case of:

- Heavy Rains, floods
- Contaminant Spills
- Levee Failures

2004 Jones Tract Levee Failure

- Silt from flooded area contaminated the Delta
- South pumps shut down until contaminant cleared
- Fixed network *insufficient* to determine safe startup
- $1M/day, 3 day shutdown

Questions:

- Where does the water go?
- How to recalibrate the Hydrodynamics?

June 2, 2004   June 5, 2004

RRLB test at Stillwater, Oklahoma

US Army Corps of Engineers / HSARPA demonstration: Rapid Repair of Levee Breach
- Rapid Repair of Levee Breach using water-filled fabric tubes
- Controlled levee breach with 125 cubic feet/s flow

RRLB test at Stillwater, Oklahoma

US Army Corps of Engineers / HSARPA demonstration: Rapid Repair of Levee Breach

- Side experiment using supply canal
- 1200' long, sinuous path
- Trapezoidal prismatic canal
- Vegetated bottom and sides
- Upstream BC: 50 cubic feet/s
- Downstream BC: height controlled by gate
- 20 runs, 6 drifters deployed upstream; gate modified in 50% of runs

Outline

Mobile Century traffic experiment

- Issues with mobile sensing in the context of traffic
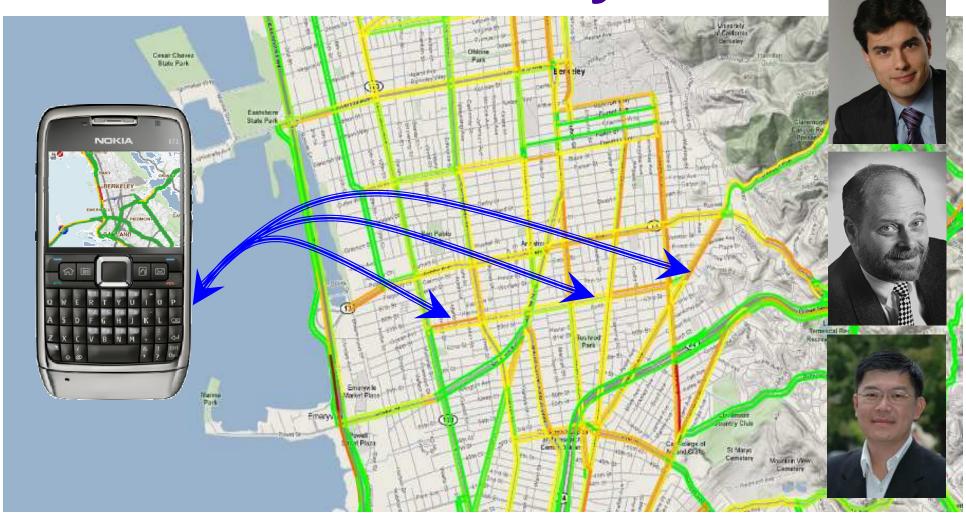- Mobile Century experiment results

Mobile floating sensor networks

- Background
- Applications

Pollution and noise estimation using smartphones
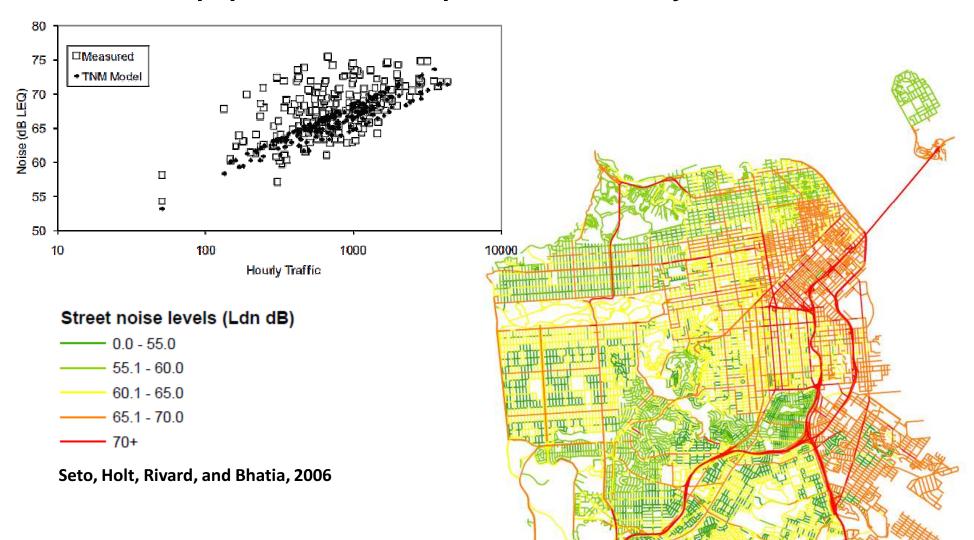
Conclusion

ClearSky

Alexandre Bayen, Steve Glaser, Edmund Seto
Systems Engineering, CEE, School or Public Health, UC Berkeley
http://traffic.berkeley.edu   http://float.berkeley.edu

Future goals (1): real time noise exposure

Inference of noise levels from traffic data (static, source: City of SF)
- 1/6 of population in SF exposed to unhealthy noise levels

Street noise levels (Ldn dB)
- 0.0 - 55.0
- 55.1 - 60.0
- 60.1 - 65.0
- 65.1 - 70.0
- 70+

Seto, Holt, Rivard, and Bhatia, 2006

Future goals (1): real time noise exposure

Inference of noise levels from traffic data (static, source: City of SF)
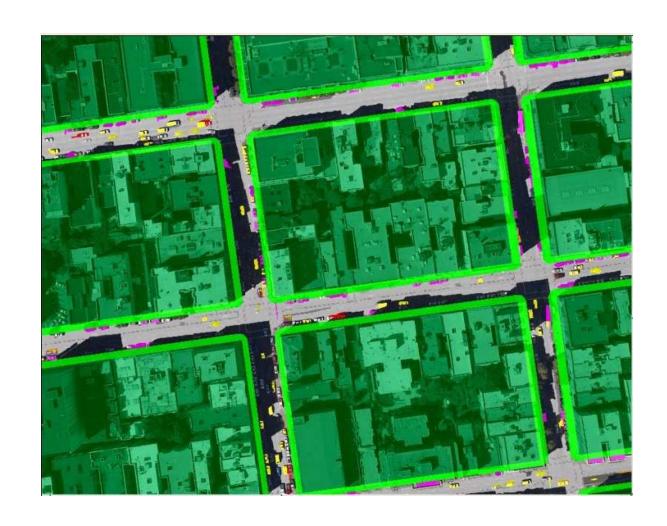
- Production of noise maps for the urban network and in the vicinity of the highway network
- Real-time map based on dynamic data
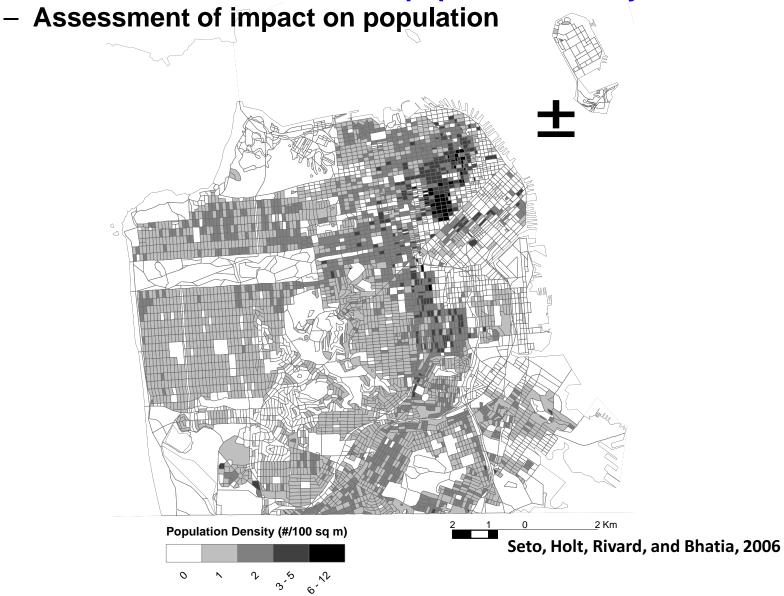- Can be used as a communication tool to rapidly inform the public

Future goals (1): real time noise exposure

Empirical data gap filling: how to understand presence of trucks?

- Aerial photographs
- Spatial data

Future goals (1): real time noise exposure
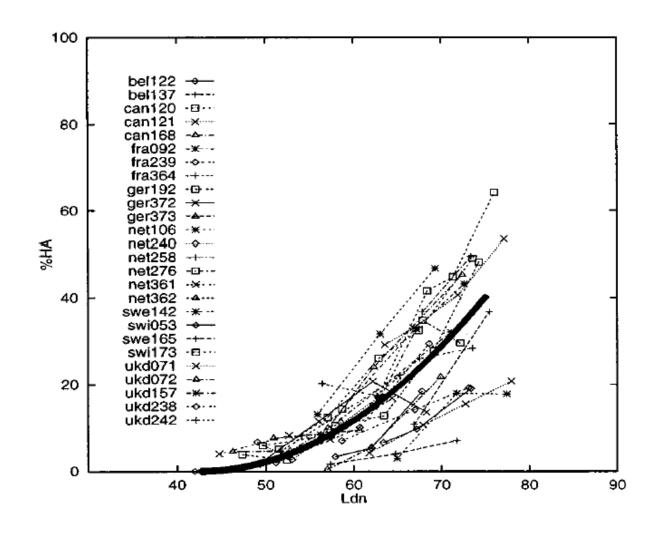
Correlation of the assessment with population density:
– **Assessment of impact on population**

Population Density (#/100 sq m)

0   1   2   3 - 5   6 - 12

2   1   0   2 Km

Seto, Holt, Rivard, and Bhatia, 2006

Future goals (1): real time noise exposure

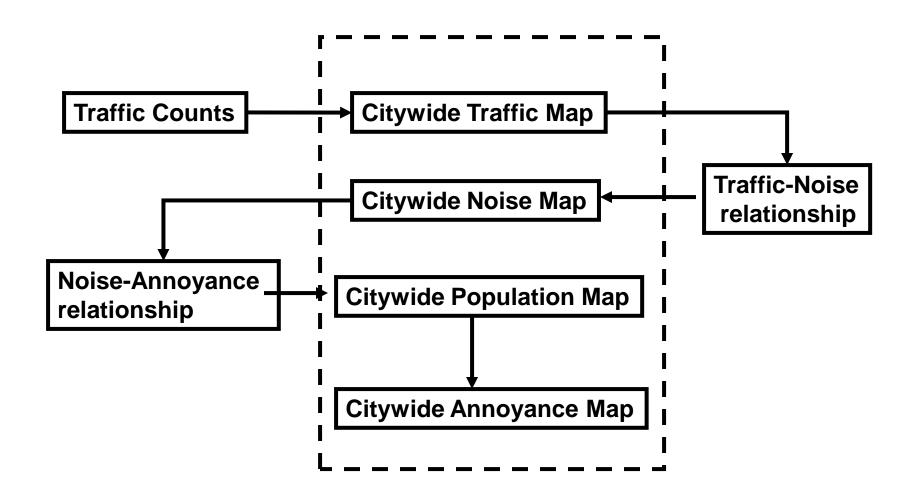**Impact maps on the population: building / using risk curves**

- – **Mortality rates can be inferred from these maps (other agents)**
- – **In a security scenario: one hour death maps, two hours, etc.**

Future goals (1): real time noise exposure

Integration process (noise, air pollution, airborne agent, etc.)
- Process will be integrated entirely in Mobile Millennium system
- Linked to population data to assess impact on population

Future goals (2): example PM2.5 aerosol

Assessment of exposure to aerosols (and other airborne agents)

- – **In the present case: emitted from cars, combustion, etc.**
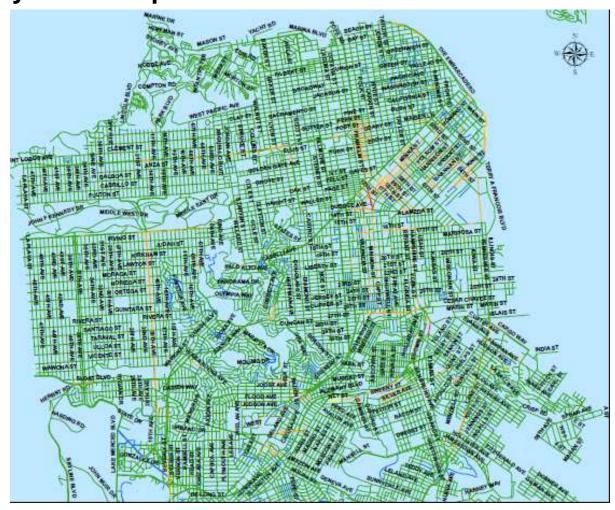- – **Study can be replicated with sensor data**

Future goals (2): example NOx aerosol

Assessment of exposure to aerosols (and other airborne agents)
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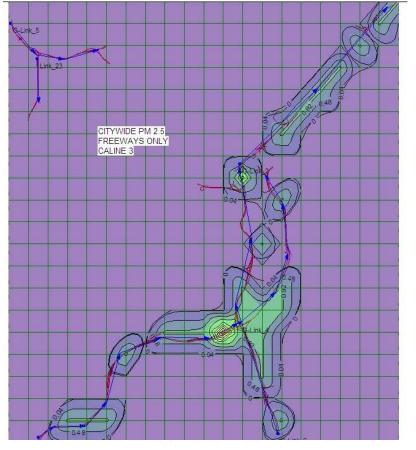- – **Study can be replicated with sensor data**

Validation procedure

Scientific approach

- Validation of the models (in the present case: Gaussian dispersion models)
- Model, assess concentration, measure, check that the measured data corresponds to the estimate
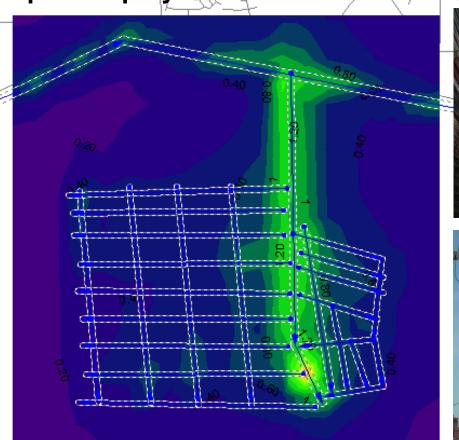- Photographs: deployment of validation sensors.

Validation procedure

Scientific approach

- – **Validation of the models (in the present case: Gaussian dispersion models)**
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- – **Photographs: deployment of validation sensors.**

Research opportunities

Outline

Mobile Century traffic experiment

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Mobile floating sensor networks

    - **Background**
    - **Applications**

Pollution and noise estimation using smartphones

Conclusion

Conclusion

Unprecedented potential for sensing the physical world...

- Almost no marginal cost for deployment (participatory sensing)
- Reliable (data quantity)

...but technical and computational challenges remain:

- User privacy (participatory sensing)
- Technical problems:

  Energy consumption (GPS)
  Context awareness for processing sensor data
  Bandwidth consumption

- Need for efficient algorithms for large scale deployments